Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://journal.nsps.org.ng/index.php/jnsps

J. Nig. Soc. Phys. Sci. 7 (2025) 2550

Journal of the Nigerian Society of Physical Sciences

# Evaluating the health risks of radionuclides in welding and fabrication workshops in Akwa Ibom State, Southern Nigeria

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**Abstract**

Welders undoubtedly experience significant health issues. The question arises: could ionizing radiation from radioactivity be responsible for these health problems, rather than solely attributing them to welding fumes and non-ionizing radiation? This study investigated the activity of primordial radionuclides, including $^{40}K$, $^{238}U$, and $^{232}Th$, and examined the health impacts of exposure to these elements within welding and fabrication environments. Using a gamma spectrometric system consisting of a NaI(Tl) detector, the study revealed significant variations in radioactivity levels such as; $^{40}K$ ranging from 158.79 to 552.53 $Bqkg^{-1}$, with an average value of 336.22 $Bqkg^{-1}$; $^{238}U$ ranged from 8.23 to 55.22 $Bqkg^{-1}$, with an average value of 27.85 $Bqkg^{-1}$, and $^{232}Th$ from 17.63 to 72.17 $Bqkg^{-1}$, with an average value of 37.97 $Bqkg^{-1}$. The trend in these variations correlated with the age and work frequency of welding sites. Although, the geology of the area should be considered in future research. In several locations, specific activity exceeded the international safe limit. Radiological parameters showed the following ranges: Radium equivalent from 49.03 to 193.69 $Bqkg^{-1}$, External Hazard from 0.13 to 0.52 $Bqkg^{-1}$, Absorbed Dose from 22.89 to 188.79 $nGyh^{-1}$, Annual Effective Dose from 0.03 to 0.11$mSvy^{-1}$, Annual Gonadal Equivalent Dose from 0.16 to 0.62 $mSvy^{-1}$, and Excess Lifetime Cancer Risk from 0.10 to 0.38 $mSvy^{-1}$. These figures further indicate that radiation levels at some welding sites exceed the world average. Therefore, further research is needed to identify other affected sites.

DOI:10.46481/jnsps.2025.2550

*Keywords:* Environmental radioactivity, Ionizing radiation, Exposure assessment, Nigeria

*Article History :*
Received: 02 December 2024
Received in revised form: 16 March 2025
Accepted for publication: 25 March 2025
Available online: 03 May 2025



Communicated by: O. J. Abimbola

## 1. Introduction

Many hazardous substances and chemical aerosols are emitted during the welding process. These substances contribute

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to various acute and chronic health issues that welders and metal workers experience. While many of these risks have been linked to welding fumes and others to non-ionizing radiation [1], the impact of ionizing radiation as a significant factor in the health challenges faced by workers has not been thoroughly examined. There is a notable similarity between illnesses caused by welding fumes, particularly respiratory issues such as lung cancer [2], and those linked to ionizing radiation from gamma emissions. Therefore, the effects of ionizing radiation should not be dismissed unless demonstrated otherwise.

Natural radionuclides are ubiquitous and constitute an integral component of the ecosystem, being present in food, air, water, soil, and even the human body [1, 3, 4]. When appropriately utilized and applied following established guidelines, these radionuclides may serve as valuable tools for addressing critical health and environmental challenges. However, uncontrolled exposure to radiation, whether due to the accumulation of primordial radionuclides or anthropogenic activities—including accidental discharges—can result in both deterministic and stochastic effects.

Several factors can lead to the potential release of ionizing radiation through the decay of primordial radionuclides, such as uranium-238, thorium-232, and potassium-40. These factors include the types of metals being welded, exposure to the earth during groundwork, and the composition of filler materials and electrodes. Ionizing radiation involves the transfer of energy that can excite an atom, knock off electrons, or alter the energy states of an atom. The uncontrolled effects of ionizing radiation can be devastating to biological tissues, potentially leading to skin cancer, lung cancer, and alterations in chromosomes, including deoxyribonucleic acid (DNA) [1].

Given the importance of welding to our economy and society, it is crucial to address potential concerns regarding the radioactivity of primordial radionuclides resulting from welding activities. Understanding the influences of this practice can significantly impact the protection and safety of welders, metal workers, the general public, and the environment. Thus, this study aims to investigate and evaluate the activity levels of uranium-238 ($^{238}U$), thorium-232 ($^{232}Th$), and potassium-40 ($^{40}K$) present in soil samples collected from selected welding and fabrication workshops in Akwa Ibom State, Southern Nigeria. This research will also assess the possible health risks associated with these exposures by accounting for radiological indices, including Excess Lifetime Cancer Risk (*ELCR*), Absorbed Dose, Effective Dose, etc.

## 2. Study area, methods and materials

### 2.1. Study area

Akwa Ibom State is an oil-producing state in the southern region of Nigeria. It is bordered by Cross River State to the east, Rivers State and Abia State to the west, and the Atlantic Ocean to the south. It is situated at latitude 409057 and longitude 708537. In addition to its rich hydrocarbon resources, Akwa Ibom State boasts the longest coastline in Nigeria, measuring 129 km.

This study randomly examines welding workshops in twelve locations across nine local government areas of the state. Some workshops, such as H, J, and K, have been in operation for about a decade, while others are relatively new and engage in fewer welding activities. Figure 1 presents a map of Nigeria, Akwa Ibom State, and Study Locations, highlighting the local government areas of the selected locations, which include Uyo, Etinan, Nsit Ibom, Eket, Esit Eket, Ibeno, Onna, Mkpat Enin, and Ikot Abasi.

It is important to note that the study could have included more welding workshops; however, some shop owners resisted participation due to their adherence to traditional beliefs and a fear of diabolism. They believe that removing soil (the ground) from their workplaces could result in misfortune or enable spiritual attacks on their business.

### 2.2. Materials

The materials used in this study included a Global Positioning System (GPS) device to locate the welding workshops, a trowel for collecting soil samples, a polythene bag for storing and transferring the samples, a fine filter to obtain smooth samples, an oven for drying the samples, and transparent plastic containers used to store them until secular equilibrium was attained. A complete gamma spectrometry system setup was utilized, including a NaI(Tl) detector and Theremino software for data acquisition and analysis of gamma-ray spectra.

### 2.3. Methodology

The soil samples used in this study were collected from welding and fabrication workshops across nine local government areas in Akwa Ibom State, Nigeria, which included both coastal and mainland LGAs. The samples were gathered from the soil's surface into waterproof bags for further processing. A Global Positioning System (GPS) was employed to document the location of each study area. After collecting the samples, they were processed following the standard methods set by the International Commission on the Effect of Atomic Radiation (IAEA), as indicated in Ref. [5].

Initially, the samples were air-dried at room temperature for twenty-four hours, then crushed, sieved, and oven-dried at 105°C for 20 minutes, followed by another twenty-four hours of air drying to eliminate any remaining moisture. Subsequently, the samples were sealed in plastic containers, labelled appropriately, and stored for 28 days to achieve secular equilibrium. After this period, the samples were ready for gamma-ray spectrometric analysis (GSA).

The gamma spectrometric system was configured as follows: A NaI(Tl) detector measuring 3 x 3 inches, housed in a cylindrical lead shield to reduce background radiation interference, was connected to a multichannel analyzer, specifically the Gamma Spectacular (model GS-2000 Pro). This entire setup was linked to a computer for data visualisation. Theremino software was used for capturing and analysing the gamma-ray spectra, while energy calibration of the detector was conducted using the RSS8 gamma source set, which is traceable to Spectrum Techniques LLC in the USA. This process involved

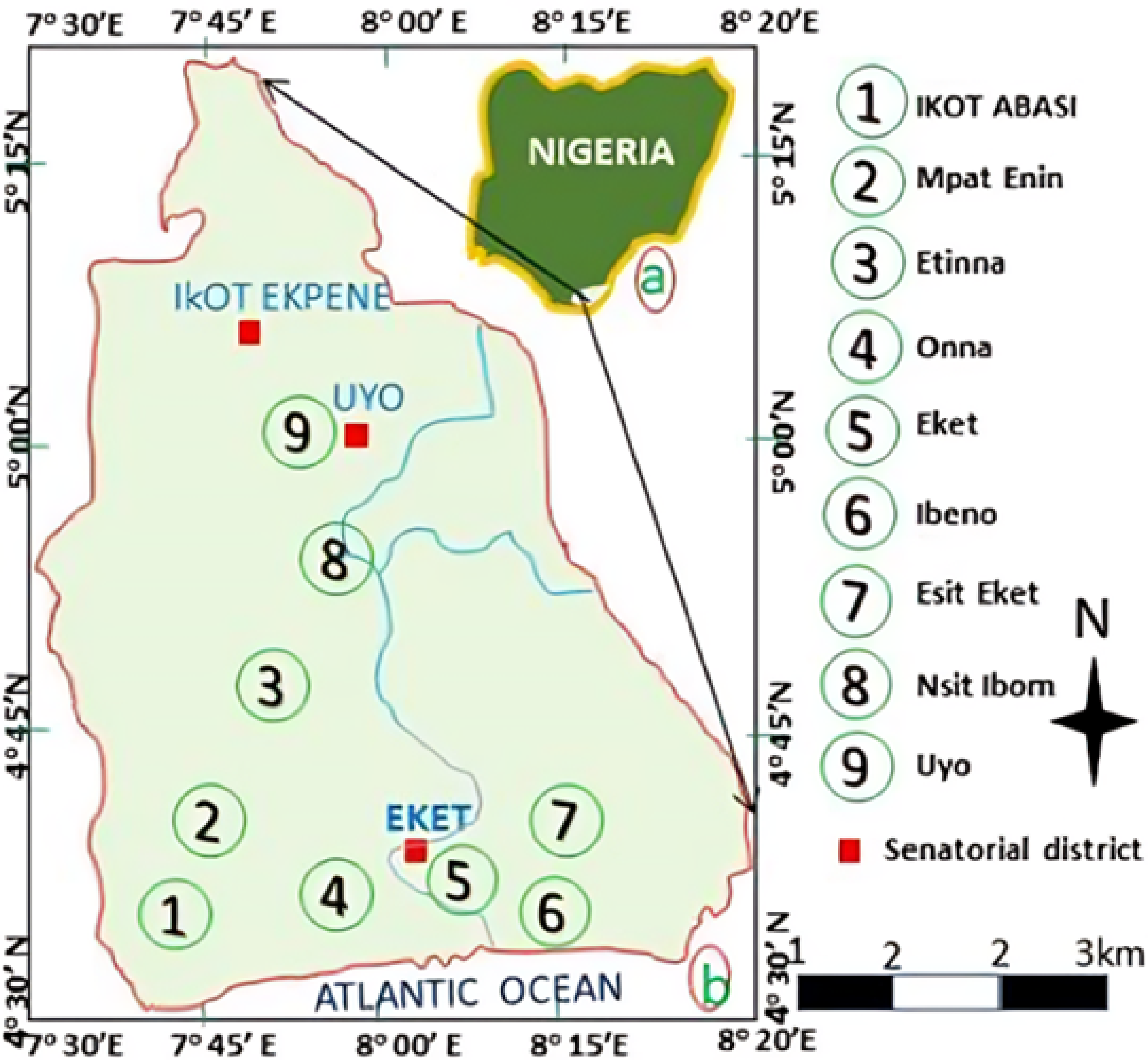


Figure 1. Akwa Ibom State and study location mapping (a) Map of Nigeria highlighting Akwa Ibom State (b) A map of Akwa Ibom state highlighting study locations of welding workshop.

recording the spectra from point sources that emit gamma rays of precisely known energies and determining the measured peak positions of these specific energies for 36000 seconds. The calibration of the detector's efficiency was also carried out using a reference standard source containing known radionuclide activities: $^{40}K$ (578.4 $keV$), $^{238}U$ (20.9 $keV$), and $^{232}Th$ (10.47 $keV$).

Additionally, an empty container was measured for 36000 *seconds* to evaluate the background gamma-ray distribution count. Each of the sealed samples, which had achieved secular equilibrium, was then placed individually on the detector for analysis. Every sample underwent counting for the same duration as the empty container. The radionuclides used to determine the sample's activity had the following energy characteristics: 1460.0 $keV$ ($^{40}K$), 1764.5 $keV$ of $^{214}Bi$ ($^{238}U$), and 2614.7 $keV$ of $^{208}Tl$ ($^{232}Th$).

The activity concentration A ($Bqkg^{-1}$) of each radionuclide identified in the sample was calculated using the formula:

$$A = \frac{C_{net}}{P_\gamma \times \varepsilon \times m \times t}, \tag{1}$$

where $C_{net}$ represents the net peak count for each radionuclide in the sample after deducting the background count from the

Table 1. GPS location of samples for each Welding site.

| Sample Code | LGA | Workshop location | |
|---|---|---|---|
| | | NORTH | EAST |
| A | Esit Eket | 04°35°843′ | 007°53°566′ |
| B | Ibeno | 04°35°975′ | 007°53°567′ |
| C | Onna | 04°36°110′ | 007°53.567′ |
| D | Mkpat Enim | 04°36°905′ | 007°53°567′ |
| E | Ikot Abasi | 04°36°725′ | 007°48°130′ |
| F | Nsit Ibom | 04°39°913′ | 007°48°130′ |
| G1 | Etinan, Market Rd | 04°83°1518′ | 007°85°189′ |
| G2 | Etinan, Market Rd | 04°83°1518′ | 007°85°189′ |
| H1 | Etinan, Osura Cres. | 04°83°1518′ | 007°85°189′ |
| H2 | Etinan, Osura Cres. | 04°83°1518′ | 007°85°189′ |
| J | Eket | 04°38°148′ | 07°56°120′ |
| K | Uyo | 04°45°095’ | 007°48°130′ |

gross count, $P\gamma$ is the absolute gamma-ray emission probability of the selected radionuclide, ε is the full energy peak efficiency obtained for each identified radionuclide, m is the mass of the sample, and t is the counting time.

### 2.4. Radiological hazards indices

Once the activity concentration of $^{238}U$, $^{232}Th,$ and $^{40}K$ was established for all samples through gamma spectrometric analysis and equation (1), the results were subsequently utilized in equations (2) to (10) to evaluate the radiological risks and health impacts parameters as outlined by the United Nations Scientific Committee on the Effects of Atomic Radiation [6]:

#### 2.4.1. Radiation hazard indices (H)

Natural radioactive materials present in the soil create an external field that the general population is exposed to. The assessment of health risks related to outdoor and indoor exposure to natural radionuclides is calculated using these indices represented as $H_{ext}$ and $H_{int}$ respectively. To ensure that the radiation hazard remains low, this value should be less than 1, and it is determined using equations (2) and (3) respectively [7–9].

$$H_{ext} = \frac{A_U}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \tag{2}$$

$$H_{int} = \frac{A_U}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \tag{3}$$

where $A_U$, $A_{Th,}$ and $A_K$ represent the specific activity concentrations of $^{238}U$, $^{232}Th,$ and $^{40}K$ in $Bqkg^{-1}$, respectively. The specific activity mass for each sample collected from the welding workshops, determined through spectrometric analysis, was inserted into equations (2) and (3) to calculate the external and internal hazards.

#### 2.4.2. Radium equivalent activity index ($Ra_{eq}$)

The total radioactivity in the soil includes contributions from $^{238}U$, $^{232}Th,$ and $^{40}K$. It has been estimated that 1 $Bqkg^{-1}$ of $^{238}U$, 0.7 $Bqkg^{-1}$ of $^{232}Th,$ and 13 $Bqkg^{-1}$ of $^{40}K$ produce an equivalent amount of gamma radiation. This estimation allows for using a single value to express the gamma output resulting from different combinations of these isotopes. The maximum permissible level for $Ra_{eq}$ in the soil is set at 370 $Bqkg^{-1}$. [8, 10, 11]. The term $Ra_{eq}$ can be defined as:

$$Ra_{eq} = A_U + 1.43A_{Th} + 0.077A_K, \tag{4}$$

where $A_U$, $A_{Th,}$ and $A_K$ maintain their standard interpretations. Likewise, the specific activity mass for each sample from the welding workshop, which was measured through spectrometric analysis, would be inserted into equation 4 to determine the resultant values.

#### 2.4.3. Absorbed dose rate (D)

Equations (5) and (6) were used to determine the outdoor and indoor absorbed dose represented as $D_{outdoor}$ or $D_{out}$ and $D_{indoor}$ or $D_{in}$ respectively, from the gamma emissions of $^{238}U$, $^{232}Th,$ and $^{40}K$ at a height of 1 meter above the ground in an open-air setting [11, 12].

$$D_{out}(nGyh^{-1}) = 0.462A_U + 0.604A_{Th} + 0.0417A_K, \tag{5}$$

$$D_{in}(nGyh^{-1}) = 0.92A_U + 1.1A_{Th} + 0.08A_K, \tag{6}$$

where, $A_U$, $A_{Th,}$ and $A_K$ maintain their standard definitions. Likewise, the specific activity mass for each sample from the welding workshop, obtained via spectrometric analysis, was input into equations (5) and (6) to derive $D$.

### 2.4.4. Annual Effective Dose (AED)

Equations (7) and (8) were used to calculate the dose received outdoors and indoors by any member of the public, with a dose conversion factor of 0.7 *Sv/Gy* and an occupancy factor of 0.2 and 0.8 for outdoor ($AED_{out}$) and indoor ($AED_{in}$) respectively [8, 11]. The outcome for the Absorbed Dose was then inserted into equations (7) and (8) to derive their results.

$$AED_{out}(mSvy^{-1}) = D_{out}(nGyh^{-1}) \times 8760h \times 0.7(SvGy^{-1}) \times 0.2 \times 10^{-6}. \quad (7)$$

$$AED_{in}(mSvy^{-1}) = D_{in}(nGyh^{-1}) \times 8760h \times 0.7(SvGy^{-1}) \times 0.8 \times 10^{-6}. \quad (8)$$

### 2.4.5. Annual Gonadal Equivalent Dose (AGED)

The impact of particular activities of $^{238}U$, $^{232}Th$, and $^{40}K$ on key organs like gonads, bone marrow, and bone cells are assessed using equation (9). Again, the specific activity derived from the spectrometric analysis of each welding workshop sample will be inserted into the equation to calculate their result.

$$AGED(\mu Svy^{-1}) = 3.09A_U + 4.18A_{Th} + 0.314A_K \quad (9)$$

### 2.4.6. Excess Lifetime Cancer Risk (ELCR)

The likelihood of developing cancer during one lifetime is affected by their exposure to radiation. An adult's cancer risk is influenced by the amount of radiation they have been subjected to Ref. [11, 13, 14]. To determine the additional lifetime cancer risk (*ELCR*), the values from equation (6) would be inserted into equation 10:

$$ELCR = AED_{out} \times DL \times RF, \quad (10)$$

where DL = Average Duration of Life (estimated to be 70) and RF = Risk factor ($Sv^{-1}$) (0.05) [8, 15].

### 2.5. Statistical analysis

This study employed a multivariable statistical approach to examine the relationship between specific activity and radiological indices in welding and fabrication environments in Akwa Ibom State, Nigeria. The Shapiro-Wilk test was conducted to assess the normality of the data distribution, revealing deviations from normality in certain variables. To further explore these relationships, Pearson correlation analysis was performed to elucidate the interdependencies among the variables. Additionally, the coefficient of variation was utilized to assess dataset variability, while principal component analysis (PCA) was applied for dimensionality reduction and to extract essential information by transforming the original variables into uncorrelated components.

Table 2. Specific activity in soil samples from welding workshops.

| Samples Code | $^{40}$K ($Bqkg^{-1}$) | $^{238}$U ($Bqkg^{-1}$) | $^{232}$Th ($Bqkg^{-1}$) |
|---|---|---|---|
| A | 204.13 | 9.78 | 17.98 |
| B | 166.55 | 13.54 | 17.82 |
| C | 252.24 | 12.97 | 22.25 |
| D | 158.79 | 9.51 | 21.92 |
| E | 425.14 | 39.5 | 47.38 |
| F | 325.98 | 36.8 | 47.04 |
| G1 | 264.21 | 12.4 | 21.8 |
| G2 | 202.42 | 8.23 | 17.63 |
| H1 | 532.76 | 49.47 | 72.17 |
| H2 | 552.53 | 55.22 | 66.62 |
| J | 531.01 | 47.75 | 57.06 |
| K | 418.82 | 39.01 | 45.98 |
| Min | 158.79 | 8.23 | 17.63 |
| Max | 552.53 | 55.22 | 72.17 |
| Mean | 336.22 | 27.85 | 37.97 |
| Sd | 143.19 | 17.48 | 19.53 |
| CV | 42.59 | 62.76 | 51.42 |

## 3. Result

Data concerning the radioactivity levels from samples collected at welding and fabrication workshops (see Table 1) in Akwa Ibom State, Nigeria, have been presented and analyzed. The findings reveal the specifics of various radioactive elements, particularly those of $^{40}K$, $^{238}U$, and $^{232}Th$ as shown in Table 2 (analysis results), alongside the computed radiological parameters derived from equations (1) to (10) displayed in Table 3.

These parameters can assess the effects of the detected specific activity on both human health and the environment. The computed parameters include the External Hazard Index ($H_{ext}$), Internal Hazard Index ($H_{in}$), Radium Equivalent Activity Index ($Ra_{eq}$), Outdoor Absorbed Dose ($D_{out}$), Indoor Absorbed Dose ($D_{in}$), Outdoor Annual Effective Dose ($AED_{out}$), Indoor Annual Effective Dose ($AED_{out}$), Annual Gonadal Equivalent Dose (*AGED*), and Excess Lifetime Cancer Risk (*ELCR*).

A comparison was made between the outcomes of this investigation and the recorded specific radioactivity from various soil including coastal, beach sediments, and other locations across the globe, as illustrated in Table 4. Furthermore, Table 5 and Table 6 presented the statistical data including the Shapiro-Wilk test, Pearson correlation principal component analysis, and coefficient of variation of all parameters with necessary figures (Figures 2 – 5).

## 4. Discussion

### 4.1. Specific activity of $^{40}K$, $^{238}U$, and $^{232}Th$ in Soil

Table 2 shows the measured specific activity of $^{40}K$ ranging from 158.79± 6.37 to 552.53 ± 14.80 $Bqkg^{-1}$, with an average value of 336.22 $Bqkg^{-1}$. For $^{238}U$, the measured activity ranges from 8.23 ± 0.94 and 55.22 ± 2.45 $Bqkg^{-1}$, with an average value of 27.85 $Bqkg^{-1}$. The activity for $^{232}Th$ ranges from

Table 3. Radiological indices from specific activity.

| Samples | $H_{ext}$ | $H_{int}$ | $D_{out}$ $nGyh^{-1}$ | $D_{in}$ $nGyh^{-1}$ | $AED_{out}$ $mSvy^{-1}$ | $AED_{in}$ $mSvy^{-1}$ | AGED $mSvy^{-1}$ | ELCR $mSvy^{-1}$ | $Ra_{eq}$ $Bqkg^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| A | 0.14 | 0.16 | 23.89 | 45.11 | 0.03 | 0.22 | 0.17 | 0.78 | 51.21 |
| B | 0.14 | 0.18 | 23.96 | 45.38 | 0.03 | 0.22 | 0.17 | 0.78 | 51.85 |
| C | 0.17 | 0.21 | 29.95 | 56.59 | 0.04 | 0.28 | 0.21 | 0.97 | 64.21 |
| D | 0.14 | 0.17 | 24.25 | 45.56 | 0.03 | 0.22 | 0.17 | 0.78 | 53.08 |
| E | 0.38 | 0.48 | 64.59 | 122.47 | 0.08 | 0.60 | 0.45 | 2.10 | 139.99 |
| F | 0.35 | 0.45 | 59.01 | 111.68 | 0.07 | 0.55 | 0.41 | 1.92 | 129.17 |
| G1 | 0.17 | 0.21 | 29.91 | 56.52 | 0.04 | 0.28 | 0.21 | 0.97 | 63.92 |
| G2 | 0.13 | 0.15 | 22.89 | 43.16 | 0.03 | 0.21 | 0.16 | 0.74 | 49.03 |
| H1 | 0.52 | 0.66 | 88.66 | 167.52 | 0.11 | 0.82 | 0.62 | 2.88 | 193.70 |
| H2 | 0.52 | 0.67 | 88.79 | 168.29 | 0.11 | 0.83 | 0.62 | 2.89 | 193.03 |
| J | 0.46 | 0.59 | 78.67 | 149.18 | 0.09 | 0.73 | 0.55 | 2.56 | 170.23 |
| K | 0.37 | 0.48 | 63.26 | 119.97 | 0.08 | 0.59 | 0.44 | 2.06 | 137.01 |
| Min | 0.13 | 0.15 | 22.89 | 43.16 | 0.03 | 0.21 | 0.16 | 0.74 | 49.03 |
| Max | 0.52 | 0.67 | 88.79 | 168.29 | 0.11 | 0.83 | 0.62 | 2.89 | 193.70 |
| Mean | 0.29 | 0.37 | 49.82 | 94.29 | 0.06 | 0.46 | 0.35 | 1.62 | 108.04 |
| Sd | 0.15 | 0.20 | 25.58 | 48.52 | 0.03 | 0.24 | 0.18 | 0.83 | 55.90 |
| CV | 51.74 | 53.92 | 51.35 | 51.46 | 51.35 | 51.46 | 51.02 | 51.46 | 51.74 |

Table 4. Radioactivity analysis in various soil environments.

| Location (s) | | $^{40}K$ $(Bqkg^{-1})$ | $^{238}U$ $(Bqkg^{-1})$ | $^{232}Th$ $(Bqkg^{-1})$ | Source |
|---|---|---|---|---|---|
| Welding & Fabrication | Min. | 158.79 | 8.23 | 17.63 | Present work |
| | Max. | 552.53 | 55.22 | 72.17 | |
| | Mean | 336.21 | 27.85 | 37.97 | |
| Mining sites in Kwara, Nigeria | Min. | 325.96 | 4.43 | 1.44 | [16] |
| | Max. | 1855.23 | 20.06 | 12.60 | |
| | Mean | 711.26 | 10.64 | 6.61 | |
| Thirthahalli, India | Min. | 18.3 | 5.1 | 5.1 | [17] |
| | Max. | 8333.4 | 79.5 | 95.3 | |
| | Mean | 175.52 | 25.99 | 17.5 | |
| Guliakhali Beach, Bangladesh | Min. | 200 | 25 | 15 | [18] |
| | Max. | 880 | 130 | 70 | |
| | Mean | - | - | - | |
| Coastal & Beach sediments, Akwa Ibom, Nigeria | Min. | 35 | 9 | 3 | [19] |
| | Max. | 250 | 44 | 72 | |
| | Mean | 145 | 23 | 36 | |
| Coastal Areas, Akwa Ibom, Nigeria | Min. | 34.65 | 5.12 | 0.03 | [20] |
| | Max. | 214.12 | 38.5 | 30.59 | |
| | Mean | 94.60 | 15.16 | 15.40 | |

$17.63 \pm 1.16$ to $72.17 \pm 2.35$ $Bqkg^{-1}$, with an average value of 37.97 $Bqkg^{-1}$. Figure 2 displays the contrast of the world global averages with the calculated averages of $^{40}K$, $^{238}U$, and $^{232}Th$. $^{40}K$ and $^{232}Th$ were found to be less than the worldwide average of 420.00 and 32 $Bqkg^{-1}$ respectively for standard background radiation levels. However, the measured specific activity of $^{40}K$ exceeded the global average in 5 out of 12 locations, namely welding sites in Ikot Abasi, Eket, Uyo, and Etinan (sample codes: E, J, K, and H1&2) respectively, while the rest were below the global limit. Similarly, specific locations like Ikot Abasi, Nsit Ibom, Eket, Uyo, and Etinan (E, F, J, K, H1&2) exceeded the global limit of $^{238}U$. Meanwhile, the mean specific activity of $^{232}Th$ was found to be above the average of 30.00 $Bqkg^{-1}$ [11], and 50% of the sample points were higher than the world average, including Ikot Abasi, Nsit Ibom, Eket, Uyo, and one of the welding sites in Etinan.$^{40}K$ is a more dominant primordial radionuclide in a welding environment.

The age of the welding sites, the frequency of work done there over the years and the properties of materials being welded including the electrode composition can influence radioactivity level at a given location. Over time, both natural and human activities have contributed to the build-up of primor-

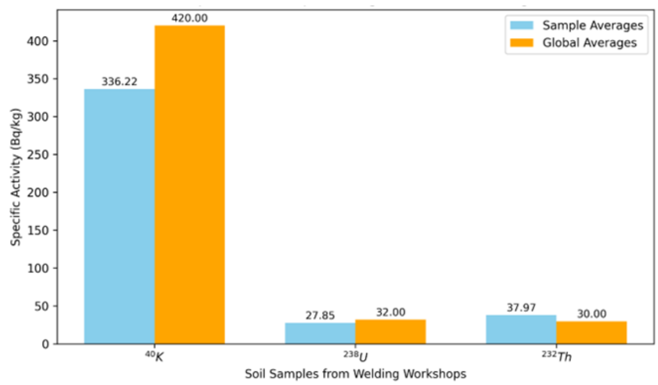


Figure 2. Comparison of sample mean with global averages.

Table 5. Test of Normality specific activity and radiological hazard indices.

| Variables | Shapiro-Wilk test | | |
|---|---|---|---|
| | Statistic | df | sig |
| $^{40}$K | 0.886 | 12 | 0.103 |
| $^{238}$U | 0.835 | 12 | 0.024 |
| $^{232}$Th | 0.850 | 12 | 0.037 |
| $H_{ext}$ | 0.828 | 12 | 0.020 |
| $H_{int}$ | 0.838 | 12 | 0.026 |
| $D_{outdoor}$ | 0.832 | 12 | 0.022 |
| $D_{indoor}$ | 0.832 | 12 | 0.022 |
| $AED_{outdoor}$ | 0.843 | 12 | 0.030 |
| $AED_{indoor}$ | 0.835 | 12 | 0.024 |
| AGED | 0.832 | 12 | 0.022 |
| ELCR | 0.831 | 12 | 0.022 |
| $Ra_{eq}$ | 0.832 | 12 | 0.022 |

where df* is degree of freedom; and sig* is p-value

dial radionuclides in soil, leading to higher specific activity and increased radiation exposure. Frequent or prolonged exposure to radiation can result in the accumulation of radionuclides in soil [21–23]. For example, the welding sites in Eket and Etinan have been operational for about a decade. In contrast, the site in Uyo has been active for about two decades with regular work which could be responsible for the higher activity concentration in that area.

### *4.2. Comparison with Previous Studies within Akwa Ibom State, Nigeria*

Comparing the current study to other research conducted by Ref. [16–20], it is logical to concede that the specific activity in specific welding and fabrication workshops can sometimes be significantly higher than the specific activity found in some well-known radioactivity areas. These include areas such as Eastern Obolo, where samples were collected from an abandoned oil operational area and an estuary where dredging activities were carried out, Ikot Abasi around Uta Ewa beach; Aluminum Smelting Plant; Upenekang in Ibeno where oil spill traces were observed, coastal soils and beach sediments along Akwa Ibom Coastline and Mining sites as reported.

Table 4 shows the minimum (Min.), maximum (Max.) and mean specific activity of various soil samples [19, 20]. The average specific activity of $^{232}U$ and $^{238}Th$ in welding and fabrication workshops was significantly higher than that of other studies. This study consistently found higher levels of $^{40}K$ across all sample points, which aligns with findings from comparable studies. This comparison suggests that welding and fabrication sites have higher levels of radioactivity particularly $^{232}U$ and $^{238}Th$, due to naturally occurring radioactive materials (NORM) and the use of materials such as heavy metal ore and electrodes containing compounds like titanium, potassium, calcium, molybdenum, chromium, nickel, and manganese. It is important to note that the level of specific activity in any given location is proportional to the impact of radiological or health hazards on humans or the environment.

### *4.3. Health Impacts Assessments*

From Table 3, this study found that the Radium equivalent activity index ($Ra_{eq}$) values ranged from 49.03 $Bqkg^{-1}$ to 193.69 $Bqkg^{-1}$, and none of the samples exceeded the recommended limit of 370 $Bqkg^{-1}$ according to Ref. [11]. Also, the external Hazard Index ($H_{ext}$) varied from 0.13 $Bqkg^{-1}$ to 0.52 $Bqkg^{-1}$ across all samples. The highest value was observed in the welding sites at Etinan (H), while the lowest value was reported at another welding site in Etinan (G2). All values were found to be lower than the recommended value of less than 1 [6]. This was similar to the internal hazard index ($H_{int}$) with values ranging from 0.15 to 0.67 $Bqkg^{-1}$. Currently, the values of $Ra_{eq}$, $H_{ext}$ and $H_{int}$ obtained in this study are all below the world averages, however, due to the accumulation of risk-dependent factors, they may become very significant and harmful soon. Despite this, other radiological indices suggest immediate health risks that warrant global concern.

The Outdoor absorbed dose rate ($D_{out}$) varied from 22.89 $nGyh^{-1}$ to 188.79 $nGyh^{-1}$, with the highest value of 188.79 $nGyh^{-1}$ reported at site H2 and the lowest value of 22.89 $nGyh^{-1}$ noted at sites G2. Welding sites in locations K, J, and H were found to be above the global average of 59 $nGyh^{-1}$. This trend across these workshops is similar to the indoor absorbed dose ($D_{in}$) with even greater risks. Workshops E, F, H, J, and K were found to be above the global average of 84 $nGyh^{-1}$. This implies that some welding workshops could emit radiation capable of causing long-term health effects, including cancer and cardiovascular diseases. The outdoor annual effective Dose ($AED_{out}$) ranged from 0.03 $mSvy^{-1}$ to 0.11 $mSvy^{-1}$, with the highest values observed at workshop H and the lowest values reported at workshops A, B, D and G2. Except for workshop E, F, J, H and K All values fall below the limit of 0.07 $mSvy^{-1}$ for outdoor exposure and 0.41 $mSvy^{-1}$ for indoor exposure ($AED_{in}$). Again this reiterates that the emission of gamma radiations from the decay of radionuclides found in some soil samples from welding sites can pose a long-term health effect to the human body. Comparing outdoor versus indoor exposure, it is far safer to carry out welding in a well-ventilated area.

Samples with the highest Annual Gonadal Equivalent Dose ($AGED$) were observed at workshop H (1&2) and J with 0.62 $mSvy^{-1}$ and 0.55 $mSvy^{-1}$, respectively, while the lowest value

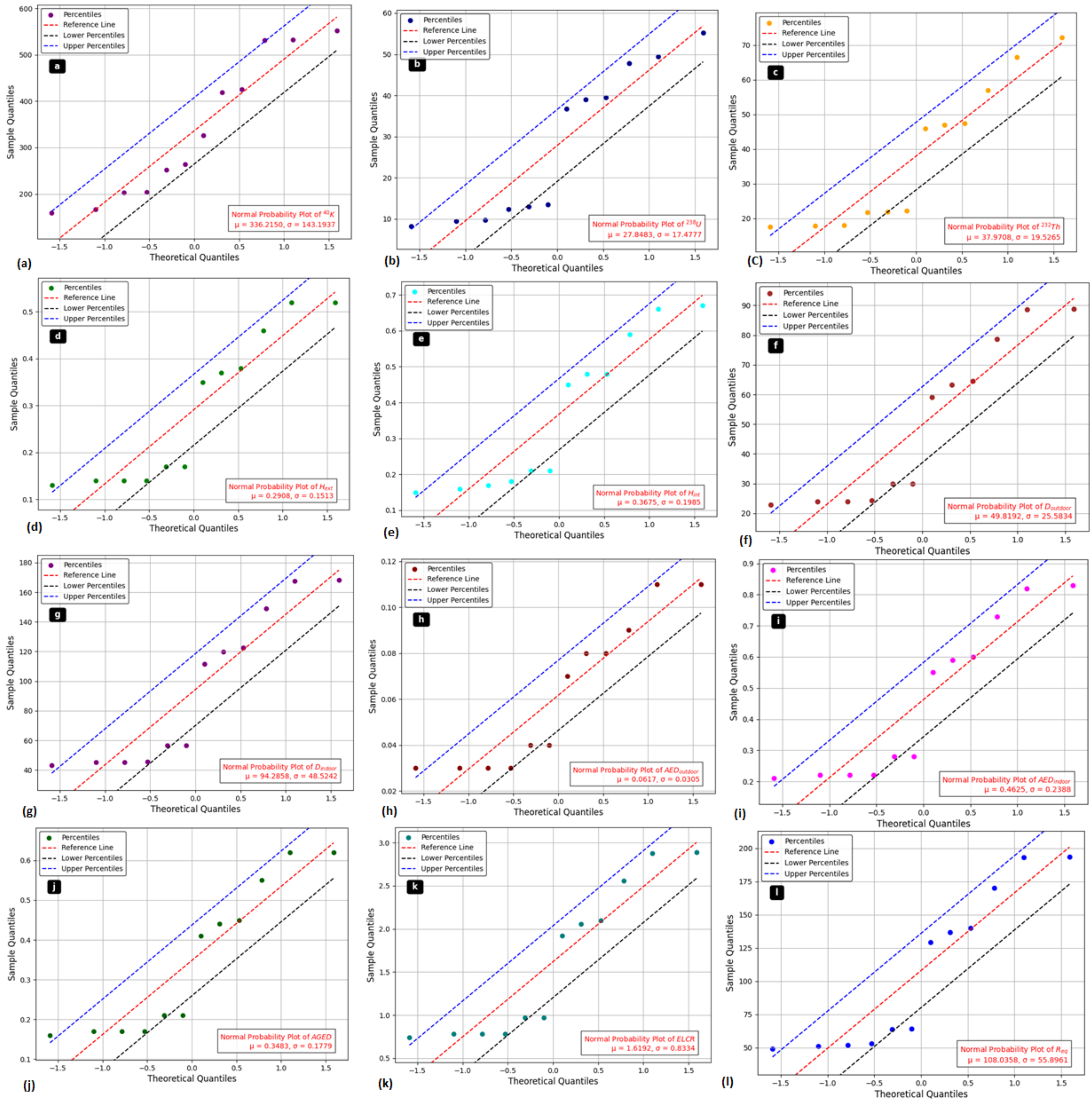


Figure 3. Normal probability distribution of a) $^{40}K$, b) $^{238}U$, c) $^{232}Th$, d) $H_{ext}$, e) $H_{int}$, f) $D_{outdoor}$, g) $D_{indoor}$, h) $AED_{outdoor}$, i) $AED\text{i}_{ndoor}$, j) $AGED$, k) $ELCR$, l) $Ra_{eq}$
.

was recorded at site G2 (i.e. outside G1's workshop) with 0.16 $mSvy^{-1}$. Workshop at Etinan (H), Ikot Abasi, Nsit Ibium, Eket, and Uyo are higher than the global average of 0.32 $mSvy^{-1}$. These results including that of Excess Lifetime Cancer Risk (*ELCR*) imply that welders could face infertility and other radiation illnesses as previously mentioned. The *ELCR* estimated from this study ranged from 0.74 $mSvy^{-1}$ to 2.89 $mSvy^{-1}$, with the highest value observed at workshop H and the lowest value noted at workshops A, B, D and G2. All values were found to be below the recommended safe limit of 3.75 $mSvy^{-1}$.

### *4.4. Statistical analysis*

#### *4.4.1. Coefficient of variation*

The coefficient of variation (CV) reveals the variability in the distribution of measured activity and radiation dose rates

Table 6. Pearson correlation coefficient matrix for specific activity and radiological indices.

| Variables | $^{40}$K | $^{238}$U | $^{232}$Th | H$_{ext}$ | H$_{int}$ | D$_{out}$ | D$_{in}$ | AED$_{out}$ | AED$_{in}$ | AGED | ELCR | Ra$_{eq}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{40}K$ | 1.00 | 0.96 | 0.96 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 |
| $^{238}U$ | 0.96 | 1.00 | 0.98 | 0.99 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| $^{232}Th$ | 0.96 | 0.98 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| $H_{ext}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $H_{int}$ | 0.98 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $D_{out}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $D_{in}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $AED_{out}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $AED_{in}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $AGED$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $ELCR$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $Ra_{eq}$ | 0.98 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

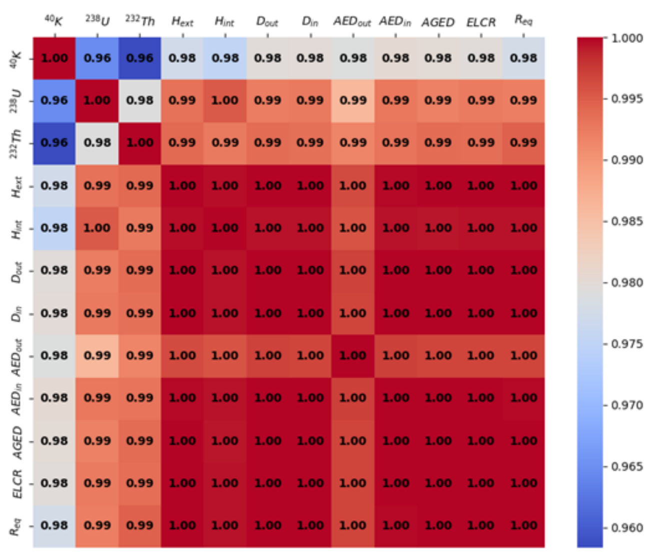


Figure 4. Pearson's correlation coefficient for specific activity and radiological indices.

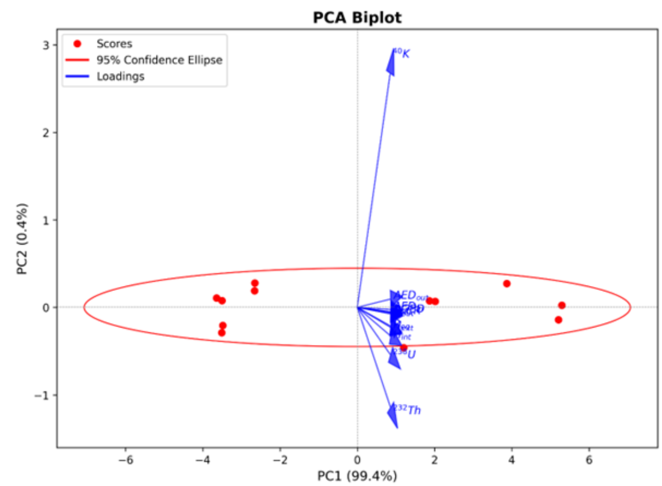


Figure 5. Graphical representation of Component 1 (99.4%) and Component 2 (0.4%)

in the study areas. If CV is less than or equal to 20%, it indicates little variability. 20% < CV ≤ 50% implies moderate variability, while 50% < CV ≤ 100% indicates high variability [24]. Therefore, the CV for $^{40}K$ indicates moderate variability at 42.59%, while $^{238}U$ and $^{232}Th$ show high variability at 62.76% and 51.43% respectively.

*4.4.2. Shapiro-wilk test*

The Shapiro-Wilk test is a statistical technique frequently used to assess if a dataset has a normal distribution because of its high accuracy and sensitivity. It is particularly helpful for small sample sizes [16]. The test results, presented in Table 5, indicate whether the data for each parameter conform to a normal distribution. Except for $^{40}K$, which probability value was greater than the significance level (sig > 0.05), suggesting that this variable follows a normal distribution, all other parameters were found to be below the significance level indicating a departure from the normal distribution. Additionally, a visual assessment of normality was conducted through a normal probability plot as shown in Figure 3a – I. This plot compares data quantiles with quantiles from a normal distribution. If data is normally distributed, the data points should lie approximately along the reference line and within the confidence bands (i.e., between the upper and lower percentiles). The normal probability plot in Figure 3a – I support the Shapiro-Wilk test findings. Data points corresponding to $^{40}K$ align closely within the percentiles. In contrast, the points for $^{238}U$, $^{232}Th$, $Ra_e$, $H_{ext}$, $H_{int}$, $D_{out}$, $D_{in}$, $AED_{out}$, $AED_{in}$, $AGED$, and $ELCR$ deviate from the straight line, indicating non-normal distribution for these variables.

*4.4.3. Pearson correlation coefficient analysis*

The Pearson correlation coefficient was used to examine the relationship, strength, and direction among the various variables. Table 6 displays the degree of correlation between the specific activity of each radionuclide and their corresponding radiological indices. Figure 4 is the pictorial representation of Table 6 called heatmap. The study shows a very high correlation (r > 0.96) among all variables indicating a strong interdependence among variables. Except $^{40}K$ all other variables exhibit a perfectly strong correlation at r = 1.

*4.4.4. Principal component analysis*

Principal Component Analysis (PCA), as illustrated in Figure 5, was employed to divide the dataset into two components. According to the analysis, these components' combined eigenvalues accounted for 99.77% of the dataset's variation. The principal component, known as Principal Component 1 (PC1), had an eigenvalue of 13.009, meaning that it accounts for almost (99.4%) of the variation. PC1 played a crucial role in capturing the underlying link, as seen by its substantial correlation with every variable under study. In contrast, PC2, the secondary component, explained 0.4% of the variance and had an eigenvalue of 0.052. Beyond what PC1 had recorded, PC2 added more information about the dataset, giving a more sophisticated view of its variance and structure.

## 5. Conclusion

This research offers important baseline information and insights into the radioactivity levels present in welding and fabrication environments. It examines the specific activity of primordial radionuclides, $^{40}K$, $^{238}U$, and $^{232}Th$ present at various welding workshops, which were subsequently compared to global background radiation averages. $^{40}K$ ranges from 158.79 to 552.79 $Bqkg^{-1}$ with an average of 336.22 $Bqkg^{-1}$, $^{238}U$ ranges from 8.23 to 55.22 $Bqkg^{-1}$ averaged 27.85 $Bqkg^{-1}$, $^{232}Th$ ranged from 17.63 to 72.17 $Bqkg^{-1}$ averaged 37.97 $Bqkg^{-1}$. The results show that specific activity in the fabrication and welding environs can vary and occasionally surpass worldwide averages. These variations have implications for radiation exposure and possible health hazards in certain areas, underscoring the need for routine environmental radiation monitoring in these contexts. An assessment of radiological parameters reveals that radiation levels in certain areas could present considerable risks. Some welding locations have exceeded the recommended limits for absorbed dose rates, annual effective doses, and annual gonadal equivalent doses. Future research in the welding environment is necessary to identify other sites or workshops with increased radioactive exposure, as it is evident that welding and fabrication workshops have significantly particular activities as compared to previous studies. The addition of materials like heavy metal ores and electrodes containing elements like titanium, potassium, calcium, molybdenum, chromium, and nickel frequently causes these sites to exhibit elevated radioactivity.

## Data availability

We do not have any research data outside the submitted manuscript file.

## Acknowledgement

The corresponding author dedicates this article to Elder and Mrs. George Ndoma in recognition of their sacrifice and unwavering commitment to ensuring that every child under their care receives a quality education. During a challenging time, Elder George Ndoma once declared, "...even if we have to sip *garri* to send our children to school, we will do it." May God bless their labour of love. Furthermore, we dedicate this work to all those striving to advance their academic journey while working tirelessly to make ends meet. Do not give up—your perseverance will pay off. May your dreams become a reality

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